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Luminescence Dosimetry: Theory and Applications

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Disclosure of COI

☑ Nothing to disclose

Contents

- Theory of luminescence dosimetry
- Application of luminescence dosimetry
- Major challenges of luminescence dosimetry

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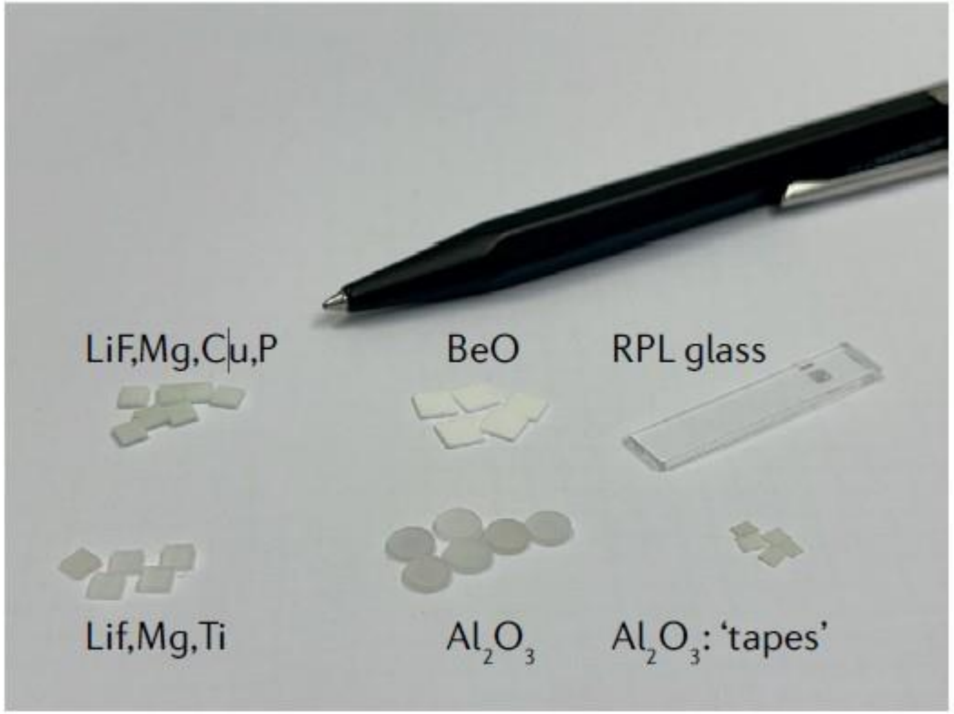
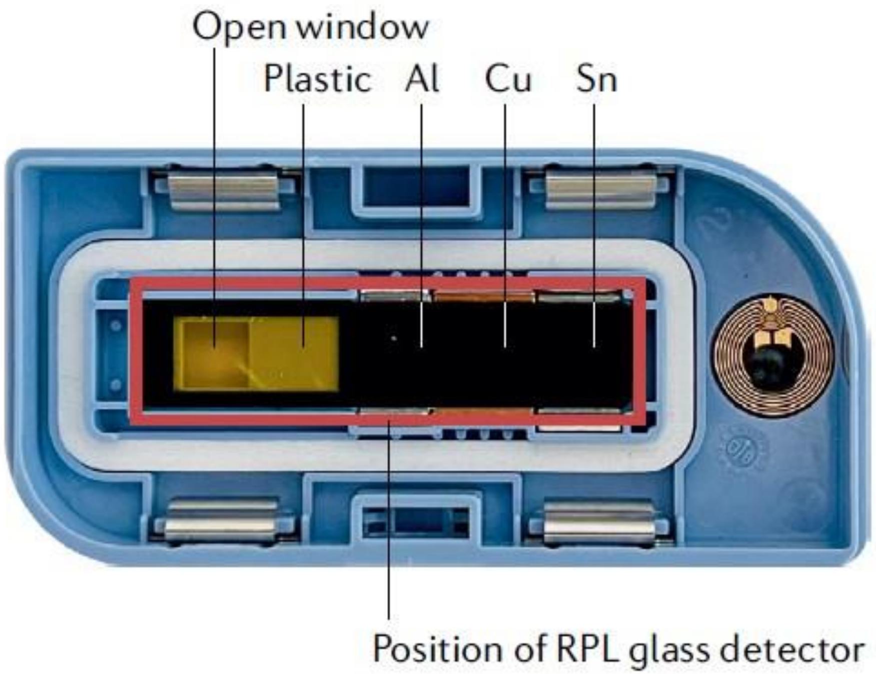
Luminescence dosimetry

Luminescence dosimetry is the process of quantifying the radiation dose using detectors that emit luminescence.





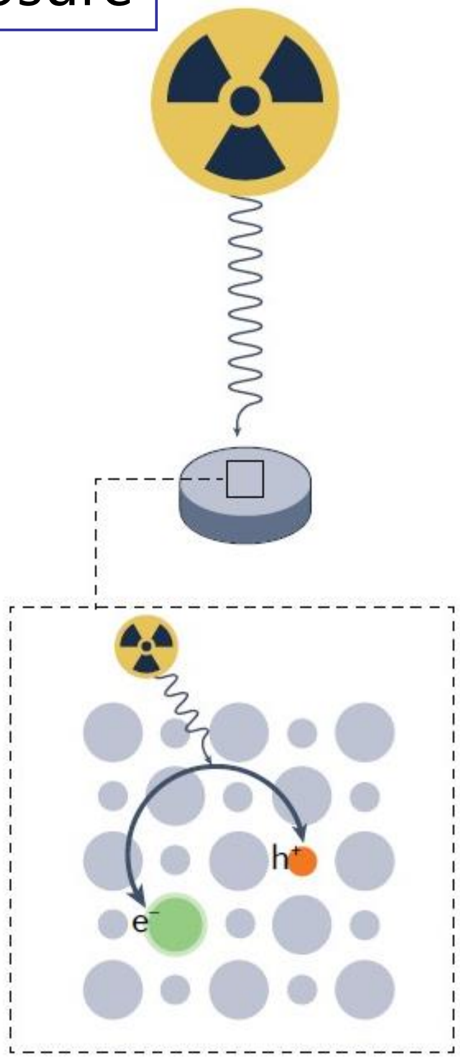
Yukihara EG, et al. Nat Rev Methods Primers (2022)

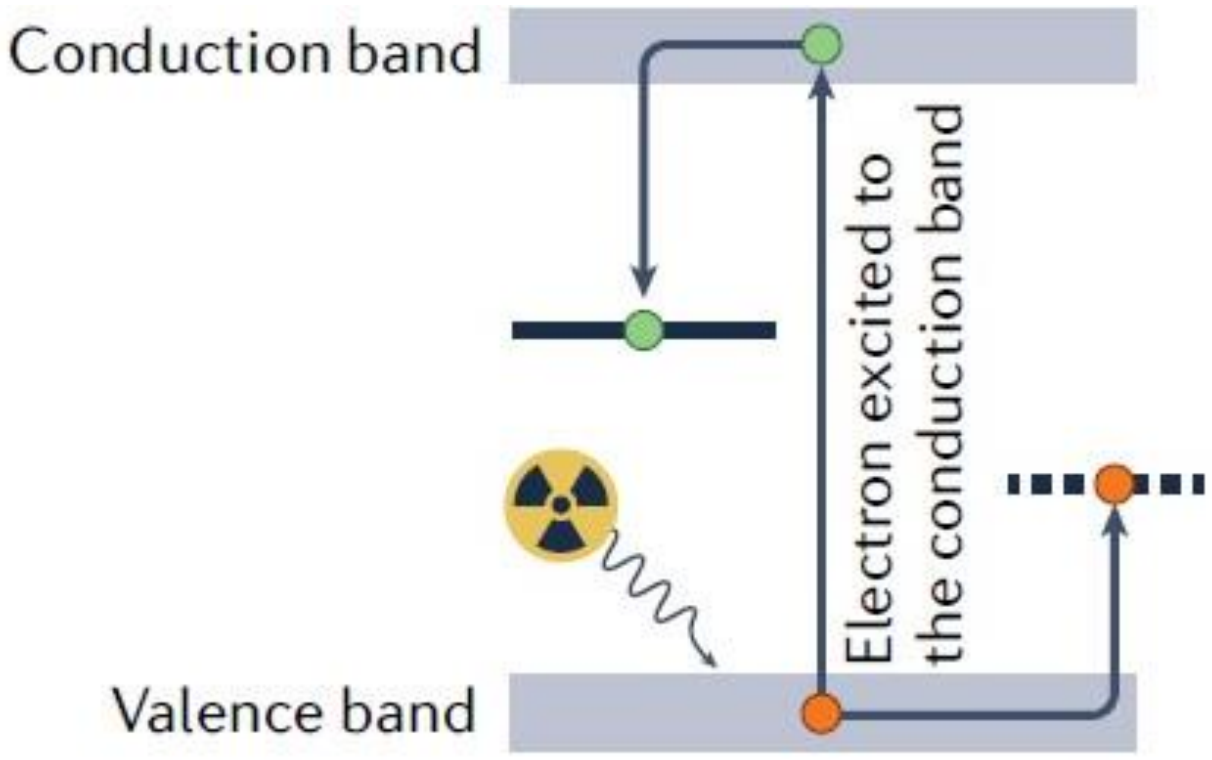
Types of luminescence dosimeters

- Thermoluminescence (**TL**) dosimeter
- Optically stimulated luminescence (**OSL**) dosimeter
- Radiophotoluminescence (**RPL**) dosimeter

Processes during exposure

Exposure

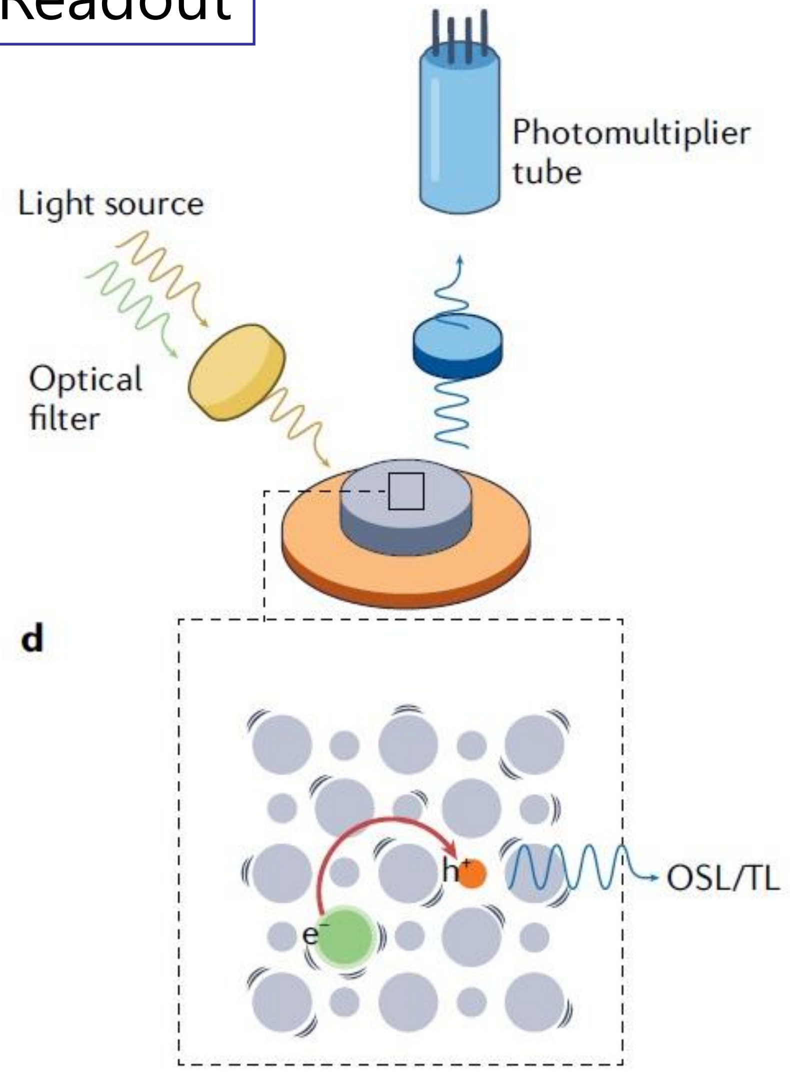


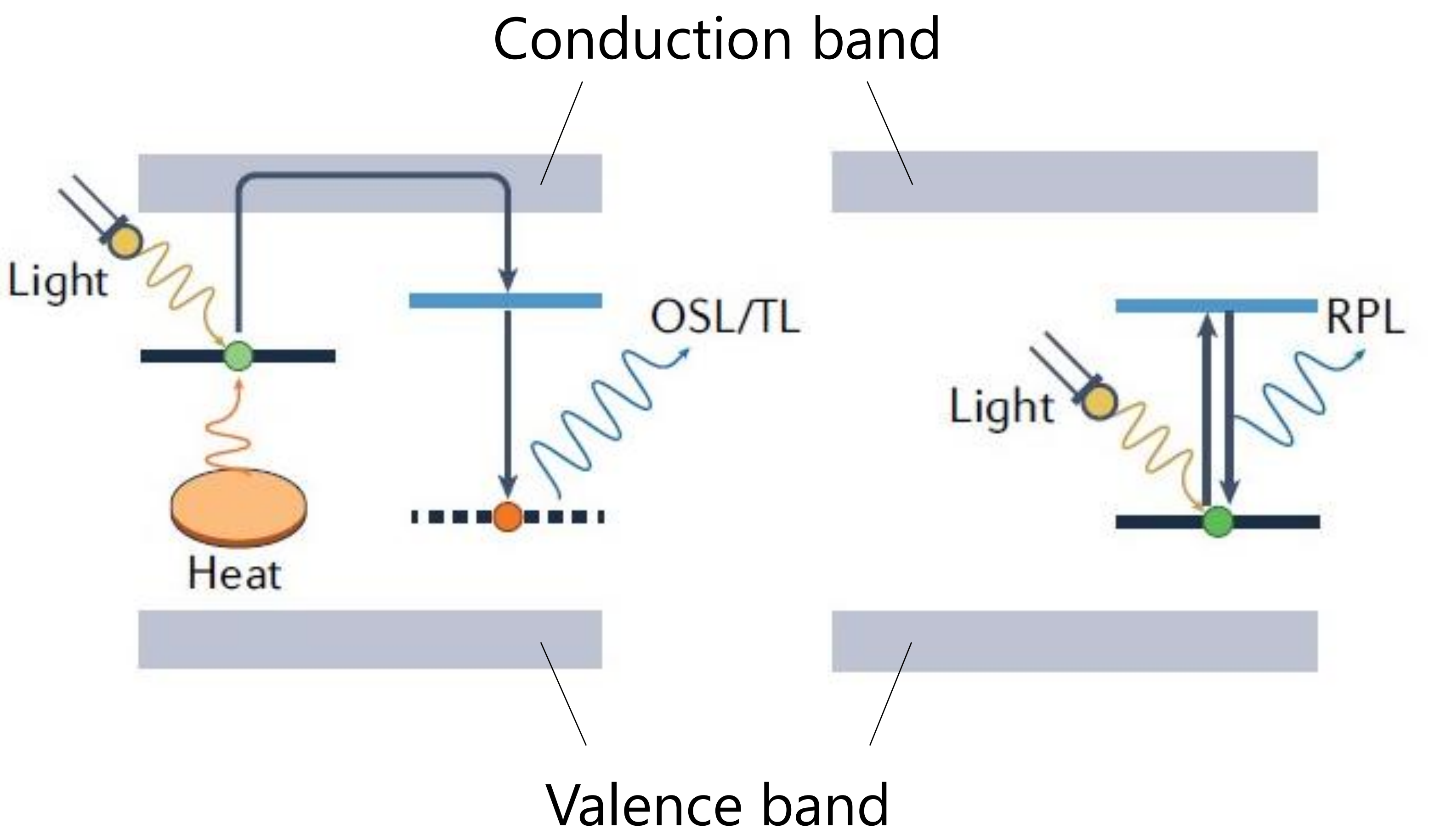


Yukihara EG, et al. Nat Rev Methods Primers (2022)

Processes during readout of a luminescence detector

Readout





Yukihara EG, et al. Nat Rev Methods Primers (2022)

Main properties of the materials in luminescence dosimetry

Material	Z_{eff} (host only)	Technique	Stimulation/ excitation	Main emission	Recommended thermal or optical treatment
LiF:Mg,Ti	8.3	TL	Heat	~410 nm (REF.[22])	400 °C for one hour + 80 °C for one day for resetting, or 400 °C for one hour + 100 °C for two hours for resetting[22]
LiF:Mg,Cu,P	8.3	TL	Heat	~370 nm (REF.[22])	240 °C for 10 min for resetting[22]
CaF_2:Dy	16.9	TL	Heat	480 nm, 575 nm (REF.[22])	450 °C for 20 min for resetting[155,156]
$CaSO_4$:Tm	15.6	TL	Heat	360 nm, 450 nm (REF.[22])	400 °C for 30 min for resetting[156]
$Li_2B_4O_7$:Cu	7.3	TL	Heat	360 nm (REF.[157])	400 °C for 30 min for resetting[156]
Al_2O_3:C	11.3	TL OSL	Heat Green	~420 nm (REF.[22]), ~335 nm (REF.[49])	900 °C for 15 min for resetting[24]
Al_2O_3:C,Mg	11.3	RPL	Red	~750 nm (REF.[52])	650 °C or ultraviolet optical treatment[52]
BeO	7.2	TL OSL	Heat Blue	~335 nm (TL)[22] ~365 nm (OSL)[158]	700 °C for 15 min for resetting[159]
Ag-phosphate glass[160]	14.8	RPL	Ultraviolet	650 nm (REF.[53])	100 °C for one hour after irradiation[71], 400 °C for one hour for resetting[53]

OSL, optically stimulated luminescence; RPL, radiophotoluminescence; TL, thermoluminescence; Z_{eff}, effective atomic number.

Yukihara EG, et al. Nat Rev Methods Primers (2022)

Data analysis

- The relationship between absorbed dose D and luminescence signal M[1)]

$$D = M_{\mathrm{corr}} \cdot N \cdot \prod_i k_i$$

  - M_{corr}: luminescence signal corrected for background, depletion, and individual sensitivity
  - N: calibration factor
  - k_i: correction factors for properties (fading, linearity, beam quality, and irradiation angle)

Kry SF, et al. Med Phys (2020)

Calibration procedures

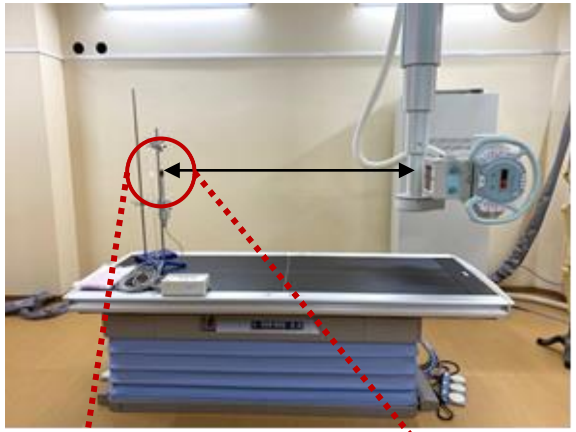
- In the reference conditions used for calibration:

$$D = M_{\mathrm{corr}} \cdot N \cdot \underbrace{\boxed{\prod_i k_i}}_{=1}$$

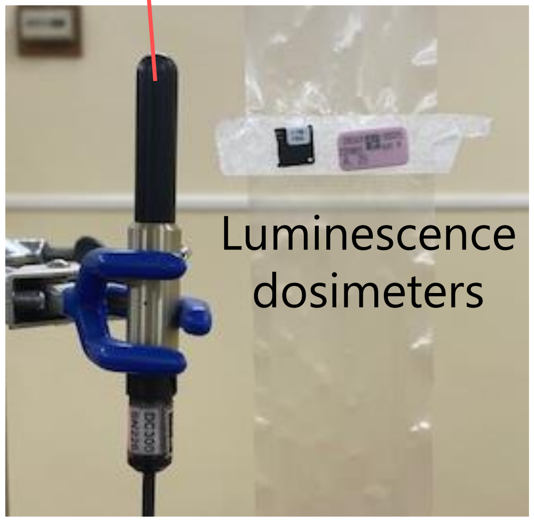
- *N* can be determined by exposing a luminescence dosimeter to conditions where *D* is known:

$$N = \frac{D}{M_{\mathrm{corr}}}$$

Calibrated ion chamber



Ion chamber



Calibration conditions

- It is recommended that the luminescence dosimeters are calibrated in conditions similar to those of the intended use.
  - Photon energy spectrum
  - Medium (air, water, etc.)
  - Intervals between irradiation and readout time

Calibration approach

- It is impractical to calibrate each dosimeter in a reference field.
- For this reason, two main approaches have been used[1]:
  - **Individual correction approach**
    - Element correction coefficients are determined for each dosimeter with respect to the mean response.
  - **Batch selection approach**
    - Dosimeters with similar sensitivities are selected.
    - Single calibration factor is applied to the entire batch.

1) Kry SF, et al. Med Phys (2020)

Source of uncertainty in luminescence dosimetry

- Sources of uncertainty in luminescence dosimetry are related to the measurement, irradiation and calibration.

- Instrumental sources of uncertainty:
  - Poisson distribution of counted photons
  - Electronic noise
  - Variations in thermal contact with the detector and heating rate
  - Variations in stimulation or excitation intensity
  - Temperature-induced variations in light detector sensitivity

Yukihara EG, et al. Nat Rev Methods Primers (2022)

Main characteristics of the luminescence dosimetry techniques

Characteristic	TL	OSL	RPL
Readout process	Thermal stimulation frees trapped charges that recombine, producing luminescence	Optical stimulation frees trapped charges that recombine, producing luminescence	Optical excitation of internal transitions within optically active centres leads to luminescence during the centre's relaxation process
Typical signal	Luminescence intensity as a function of temperature with peaks corresponding to different trapping centres; peak intensity and area are proportional to the absorbed dose	Luminescence intensity as a function of stimulation time showing an exponential-like decay, with decay rate proportional to stimulation intensity; the peak intensity and area are proportional to the absorbed dose	Constant luminescence intensity, proportional to excitation intensity and absorbed dose; for pulsed excitation, luminescence decays between excitation pulses
Signal loss with readout?	Yes	Yes, but signal loss per readout can be controlled	No
Emission wavelength	Characteristic of the luminescence centres	Characteristic of the luminescence centres; ideally shorter than the stimulation wavelength	Characteristic of the optically active centres; wavelength longer than the excitation wavelength (Stokes shifted)

OSL, optically stimulated luminescence; RPL, radiophotoluminescence; TL, thermoluminescence.

Yukihara EG, et al. Nat Rev Methods Primers (2022)

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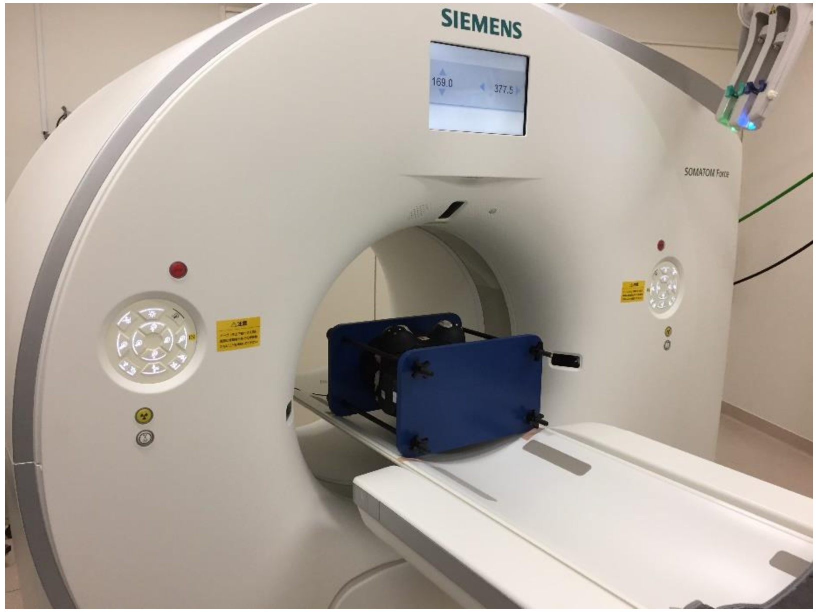
Absorbed doses with different tube voltages: Methods (1)

- Absorbed doses at nipple level of the female phantom were obtained using RPL dosimeters.

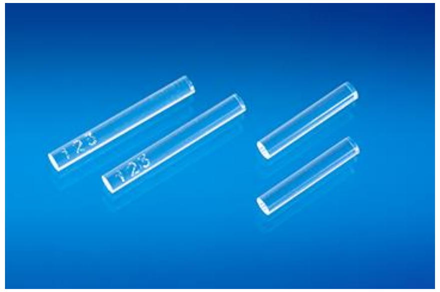
Anthropomorphic phantom:
RAN-110
(The Phantom Laboratory)

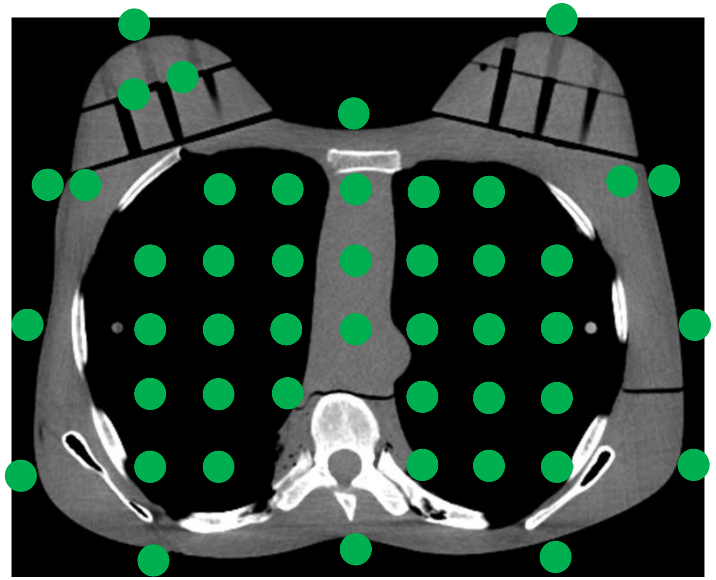


192-slice CT scanner:
SOMATOM Force
(Siemens Healthineers)

Absorbed doses with different tube voltages: Methods (2)

- Numbers of RPL dosimeters:
  - Lung × 27
  - Soft tissue × 5
  - Skin × 12
  - Right breast × 2
  - Background × 2





● Location of dosimeter

- Absorbed dose at each measurement point (D_{m}):

$$D_{\mathrm{m}} = (M_{\mathrm{i}} - M_{\mathrm{b}}) \cdot N \cdot \frac{(\mu_{\mathrm{en}}/\rho)_{\mathrm{soft}}}{(\mu_{\mathrm{en}}/\rho)_{\mathrm{air}}}$$

M_i: Readout value from i-th dosimeter

M_{b}: Mean background readout value

N: Correction factor for i-th dosimeter

μ_{en}/ρ: Mass energy absorption coefficient (s, soft tissue; a, air)

Absorbed doses with different tube voltages: Methods (3)

- Acquisition parameters for kV comparison:

Parameter	70 kV	80 kV	100 kV	120 kV
Effective mAs	854	520	249	150
Acquisition (mm)	192×0.6	192×0.6	192×0.6	192×0.6
Rotation time (s/rot)	0.5	0.5	0.5	0.5
Pitch	0.6	0.6	0.6	0.6
$CTDI_{vol}$ (mGy)	10.0	10.0	10.0	10.1

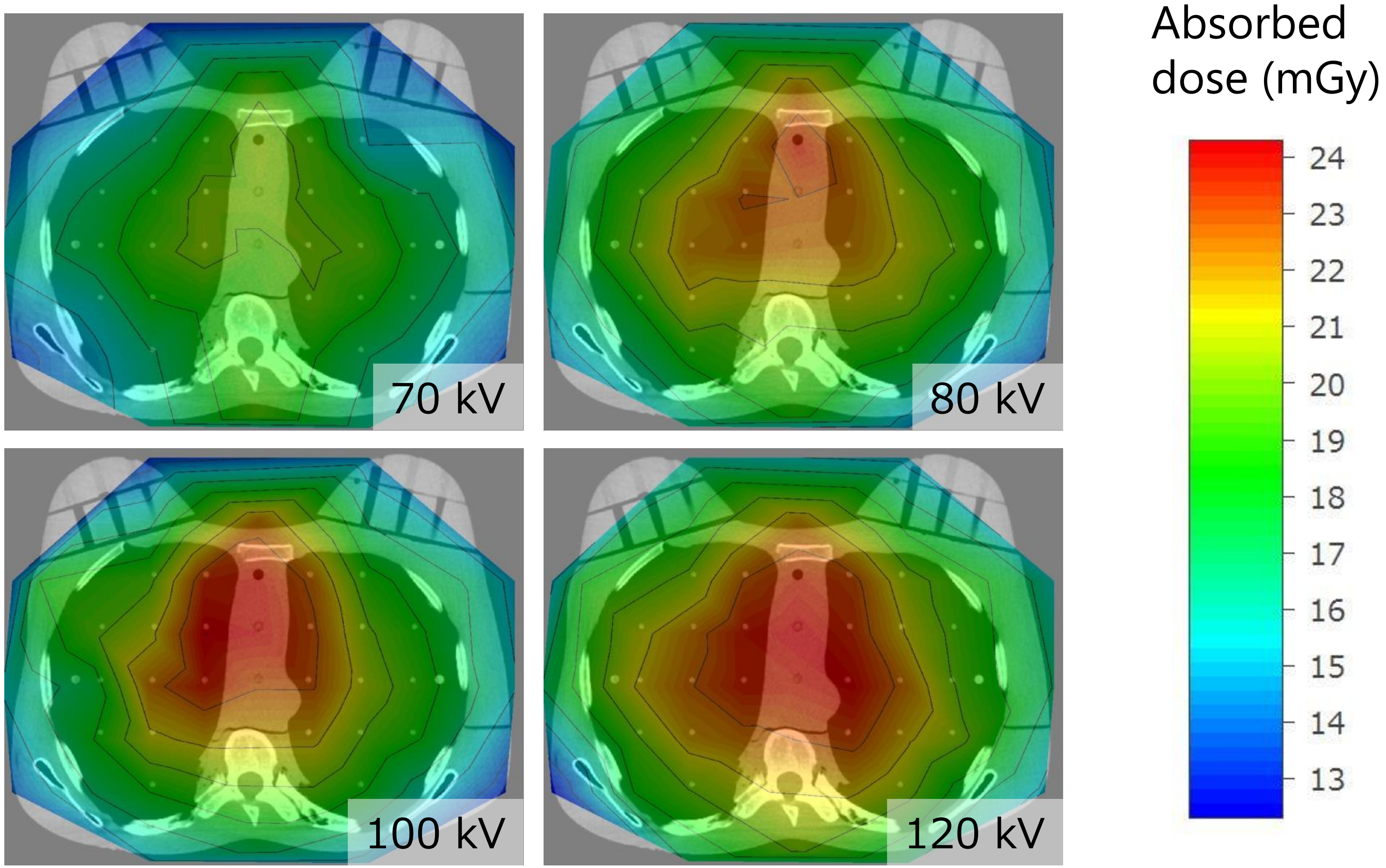
Absorbed doses with different tube voltages: Results (1)

- Calibration factors for RPL dosimeters:

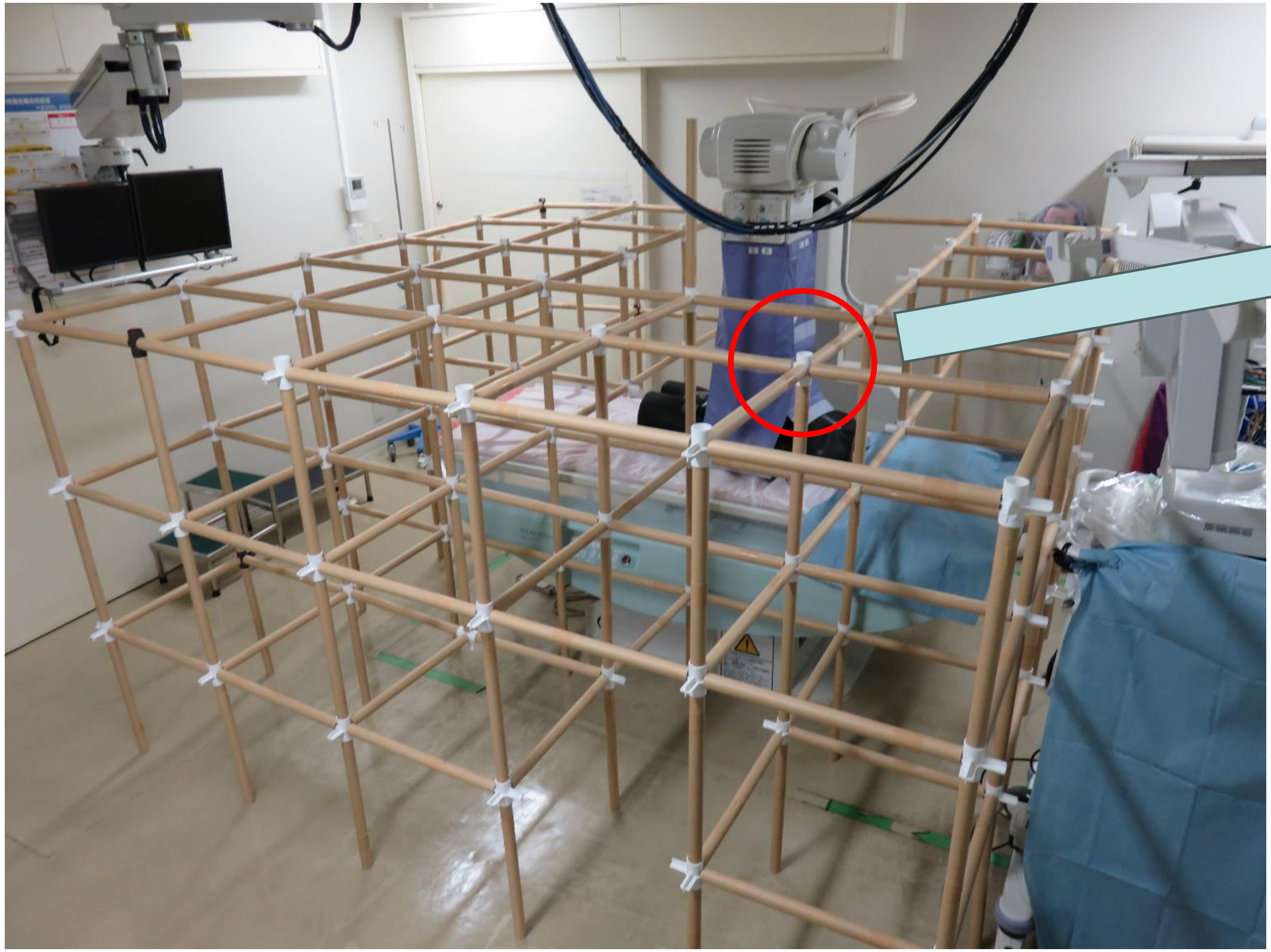
Tube voltage (kV)	Calibration factor (Mean ± SD)
70	0.28 ± 0.01
80	0.30 ± 0.01
100	0.32 ± 0.01
120	0.35 ± 0.01

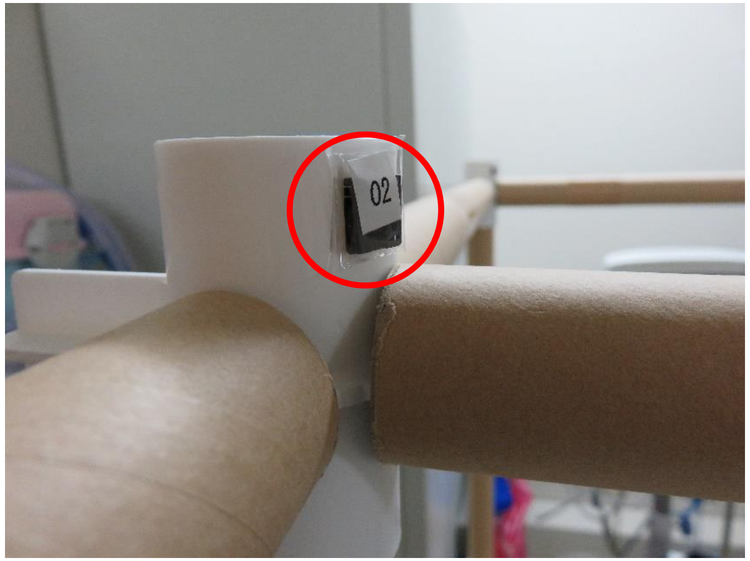
Absorbed doses with different tube voltages: Results (2)

- Dose distributions with different tube voltages:



Effect of radioprotective curtain: Methods

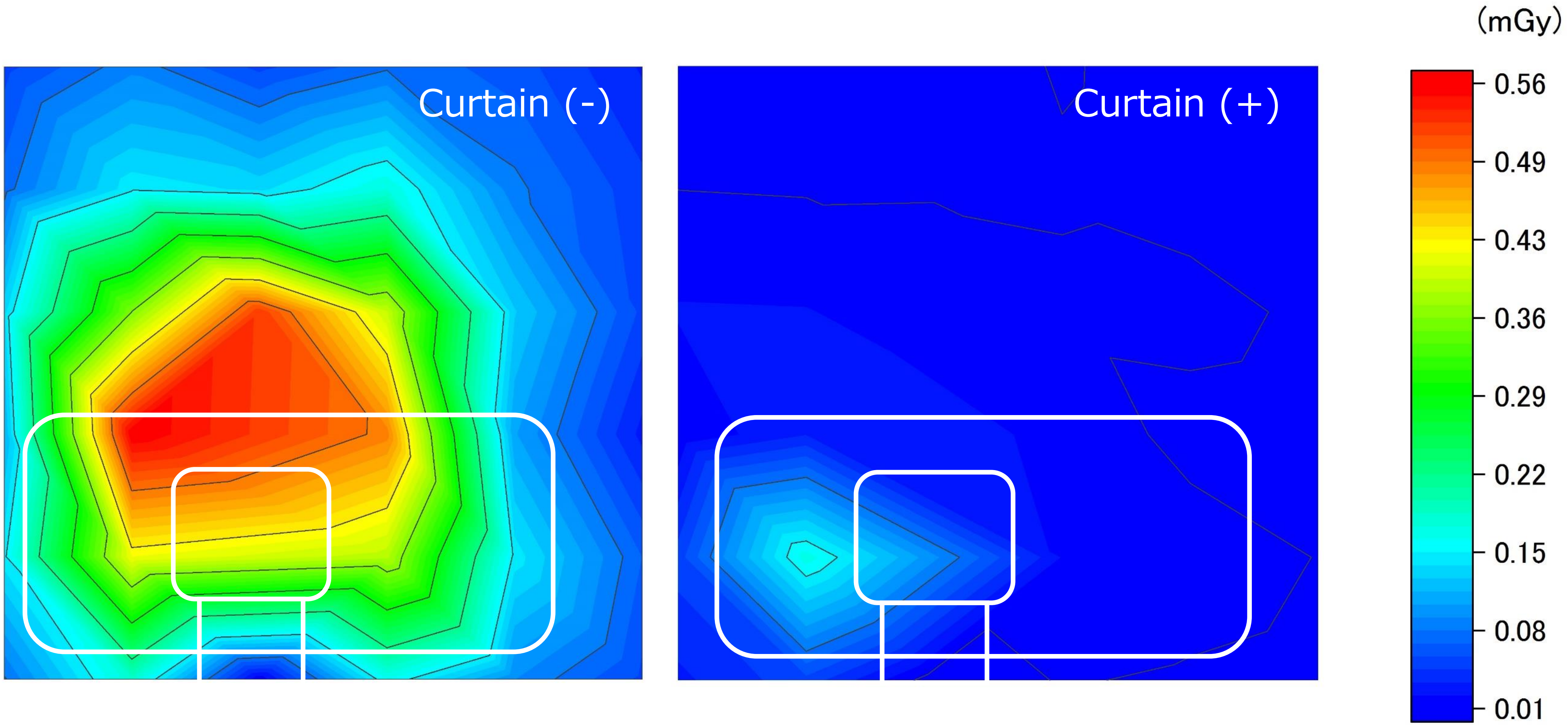




Small OSL dosimeters were attached to the connection parts of the paper pipes, facing the direction of the radiation source.

Hirosawa A, et al. Nihon Hoshasen Gijutsu Gakkai Zasshi (2020)

Effect of radioprotective curtain: Results



Hirosawa A, et al. Nihon Hoshasen Gijutsu Gakkai Zasshi (2020)

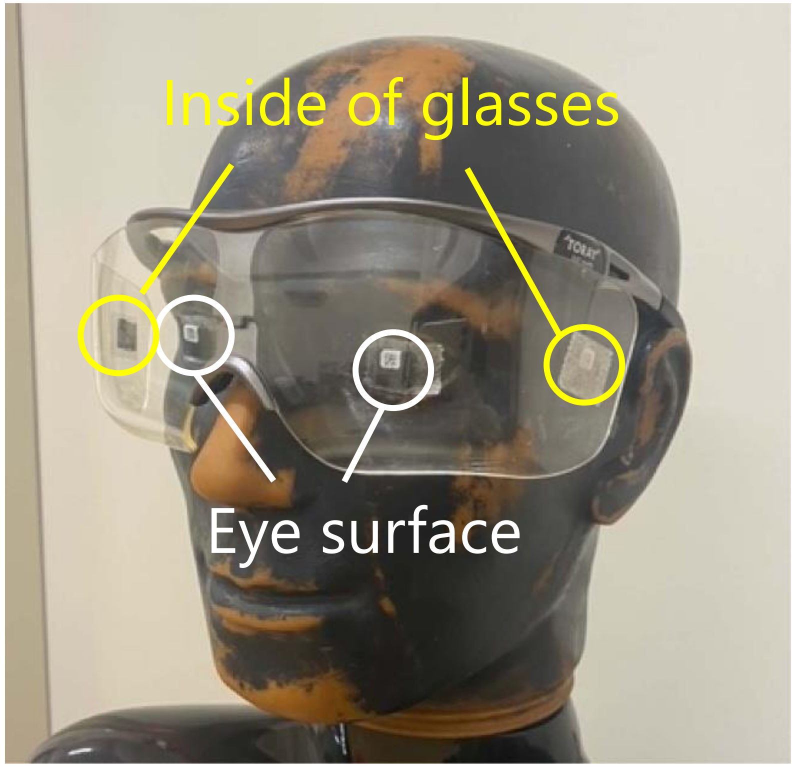
Eye lens dose for medical staff during CT: Methods

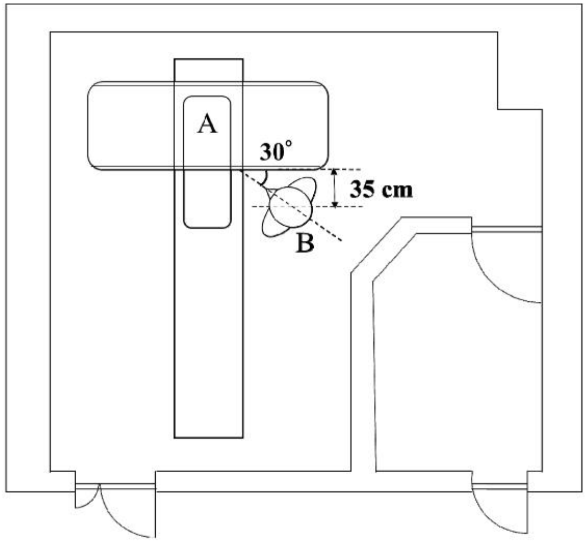
Glasses 1

Glasses 2

Glasses 3

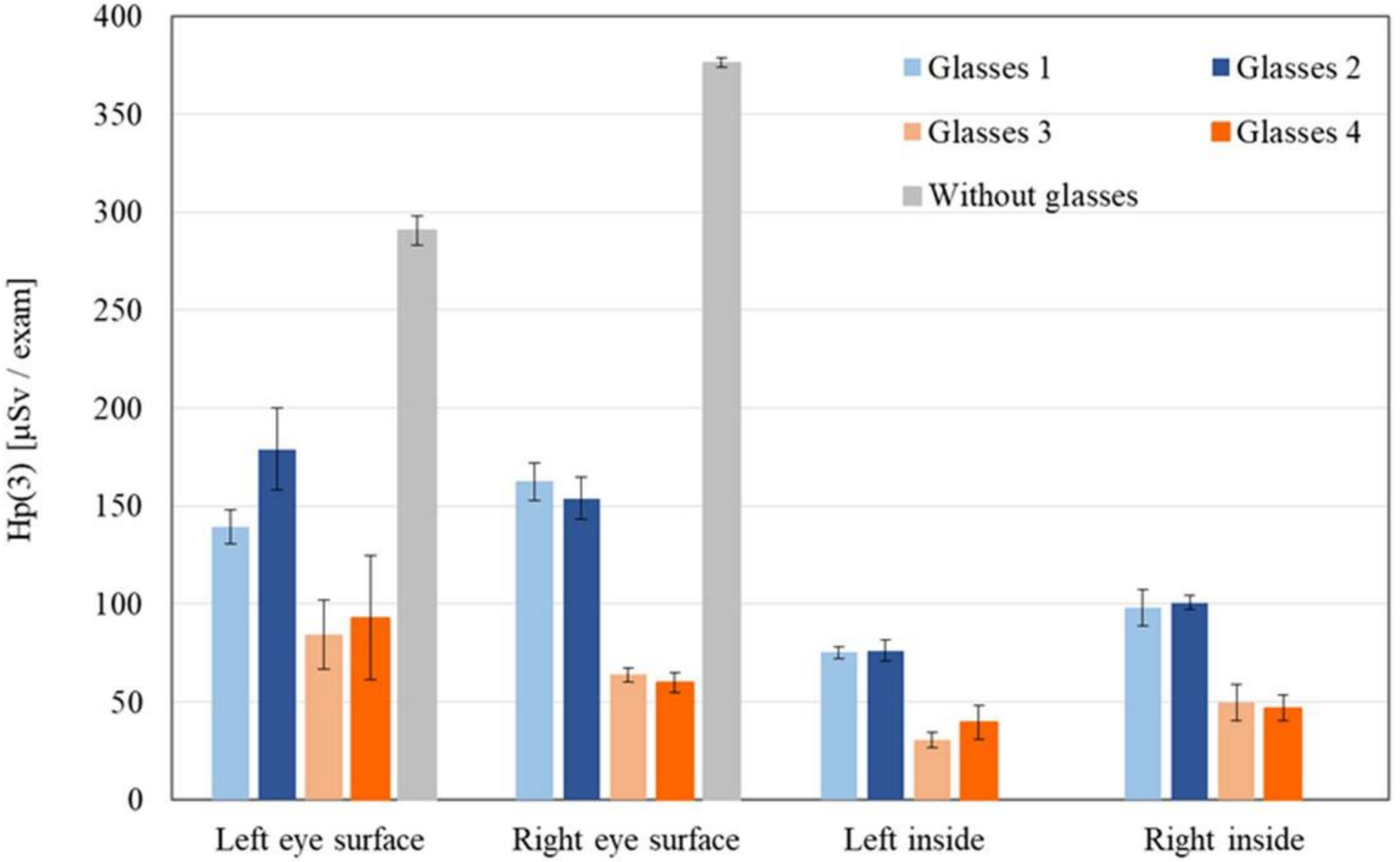
Glasses 4





Fukushima K, et al. J Radiol Prot (2023)

Eye lens dose for medical staff during CT: Results



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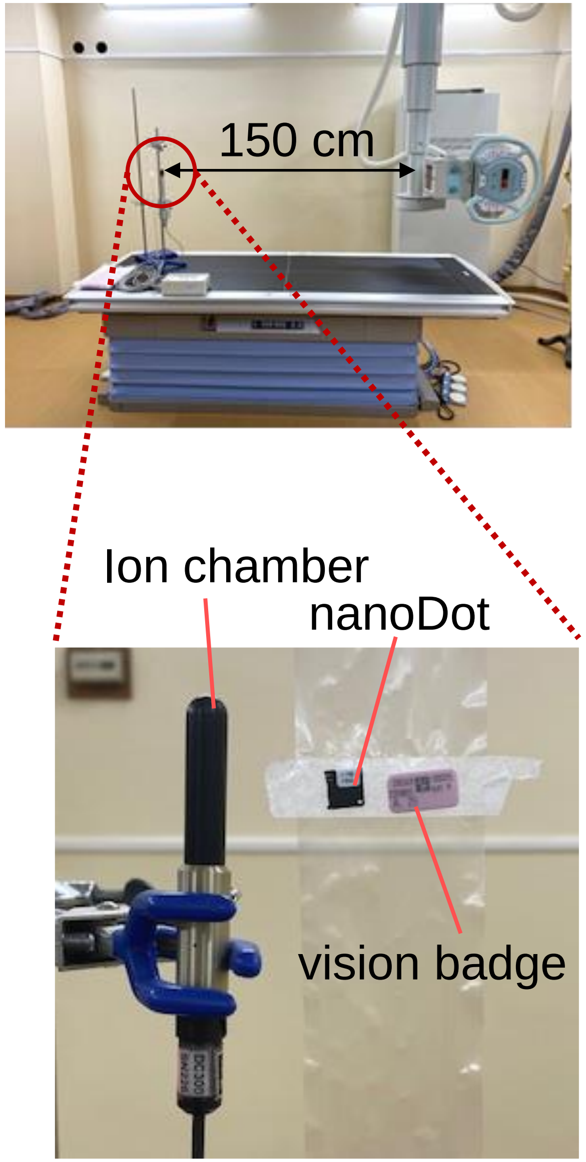
Energy dependence: Methods



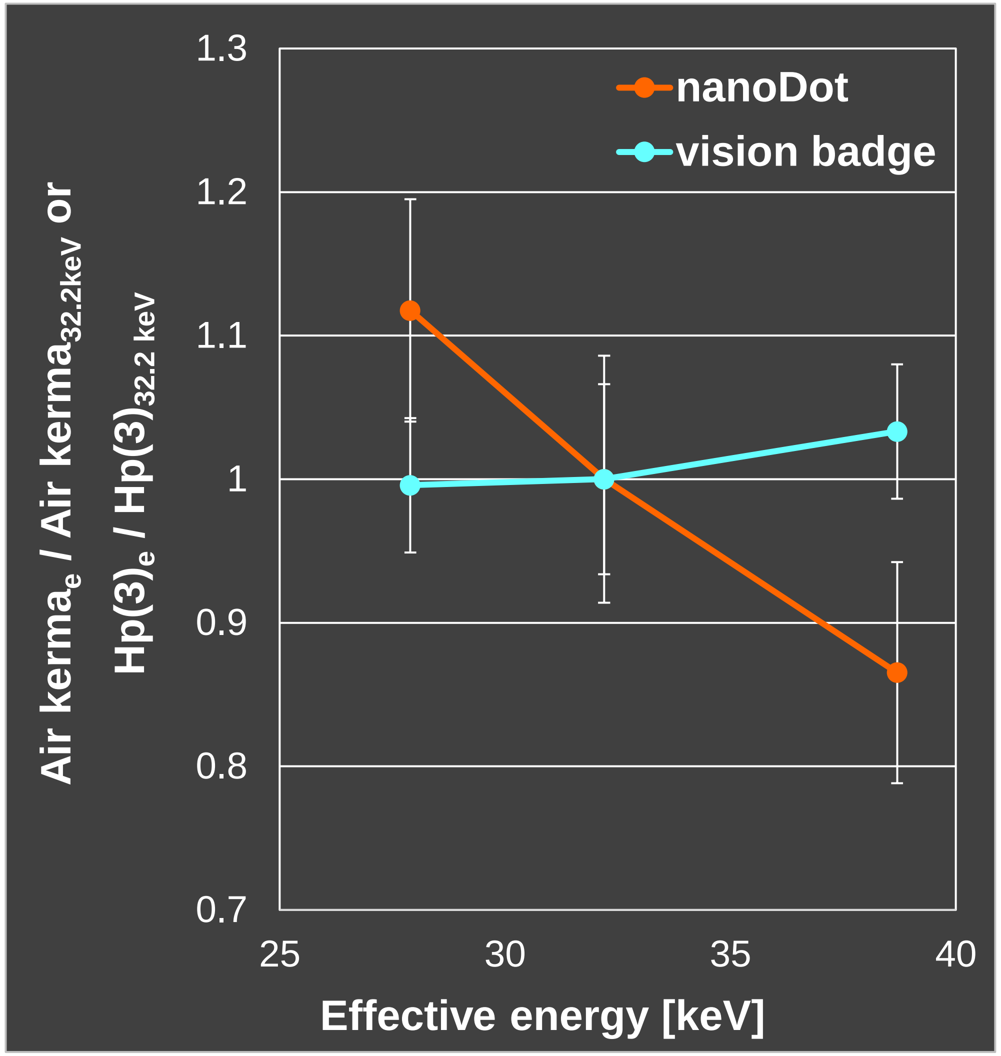
Tube voltage (kV)	Effective energy (keV)	Tube current (mA)	Irradiation time (ms)
50	**27.9**	500	125
80	**32.2**	400	63
120	**38.7**	250	50

Measurements were performed three times under the same conditions, and the nanoDot dosimeters were read three times.

⇩

Relative values were calculated by dividing the Hp(3) at each effective energy by the Hp(3) at 32.2 keV.

Energy dependence: Results



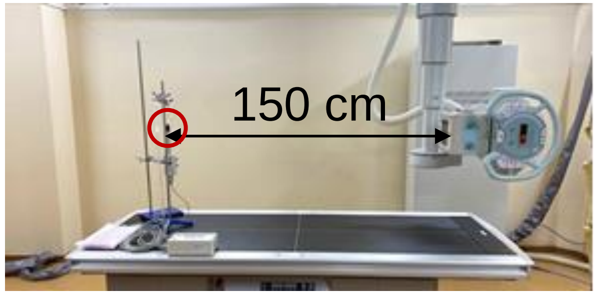
nanoDot 

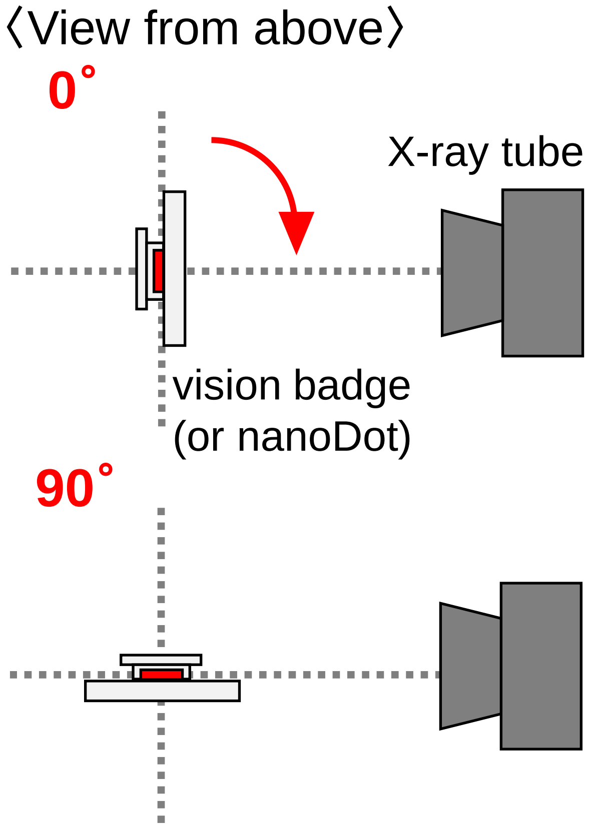
When the effective energy was increased from 27.9 to 38.7 keV, the sensitivity was **22.6%** lower.

vision badge 

When the effective energy was increased from 27.9 to 38.7 keV, the sensitivity was **3.8%** higher.

Angular dependence: Methods





Tube voltage (kV)	Effective energy (keV)	Tube current (mA)	Irradiation time (ms)
70	30.7	200	400

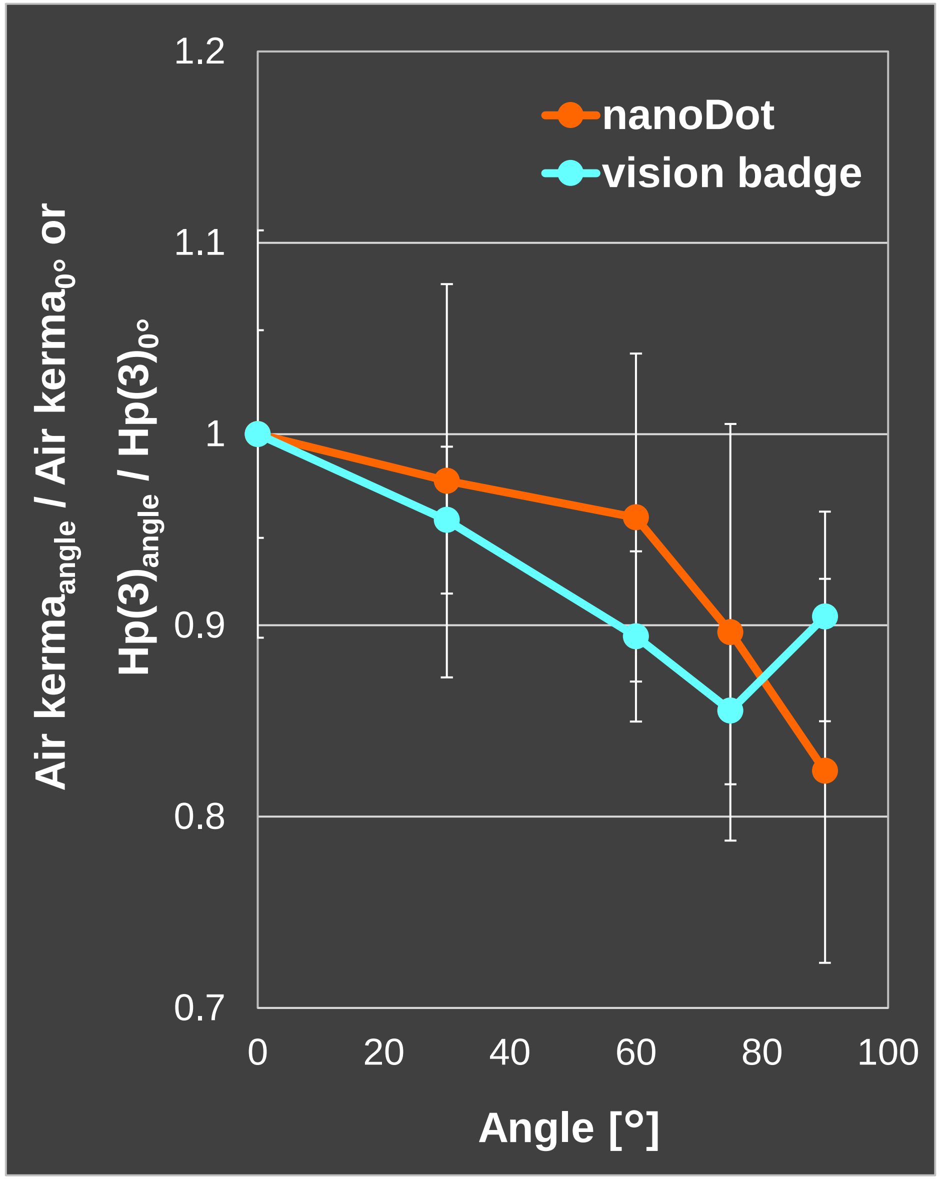
The front surface of vision badge and nanoDot facing the X-ray tube were set to **0°**, and dosimeters were rotated clockwise to **30°**, **60°**, **75°**, and **90°**.

Measurements were performed three times under the same conditions, and the nanoDot dosimeters were read three times.

⇩

Relative values were calculated by dividing the Hp(3) at each angle by the Hp(3) at 0°.

Angular dependence



nanoDot 

When the angle was changed from 0° to 90°, the sensitivity was **17.6%** lower.

vision badge 

When the angle was changed from 0° to 75°, the sensitivity was **14.5%** lower.

However, when the angle was changed from 75° to 90°, the sensitivity increased by **4.9%**.

Summary

- For luminescence dosimetry, storage phosphors have been used including TL, OSL, and RPL dosimeters.
- The emission intensity can be converted into absorbed dose, kerma, and personal dose equivalent by calibrating these dosimeters and applying correction factors.
- Major challenges of the luminescence dosimetry for medical imaging field are the energy and angular dependence of the dosimeters.